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Quantifying, Predicting and Exploiting Environmental and Acoustic Fields and Uncertainties

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LONG-TERM GOALS

The overall goal is to *better understand, model, forecast and exploit environmental and acoustic fields and uncertainties for efficient sonar operations and to research, integrate and demonstrate end-to-end prediction and DA systems to do so.*

OBJECTIVES

Our specific objectives for the main four years of the DRI are to:

- Carry out scientific computations and process/sensitivity studies to better understand dynamics, predictabilities and uncertainties in the East China Sea (ECS) and the continental shelf and slope northeast of Taiwan, especially the Cold Dome and its interactions with the meandering Kuroshio, Taiwan Strait currents, atmospheric forcing, barotropic tides, and internal tides and waves.
- Further research and implement multiply nested and coupled environmental and acoustic models.
- Develop uncertainty estimation schemes using ESSE ensembles and new prognostic equations.
- Assimilate ocean physics data and utilize coupled data-model misfits to improve models including acoustic and seabed parameters
- Carry out Observation System Simulation Experiments to estimate some observation system properties and use adaptive sampling schemes to optimize the placement of sensor systems for the reduction of uncertainty and best exploitation of the environment.
- Research smaller-scale non-hydrostatic modeling and link our regional modeling effort to larger-scale modeling, including the use of acoustic measurements in deep waters.
- Participate to real-time exercises, issue data-driven forecasts and recommendations to exploit uncertainties, and so develop end-to-end real-time multi-model systems.
- Collaborate with the DRI-QPE team.

APPROACH

The regional ocean dynamics and modeling focus is the continental shelf and slope northeast of Taiwan, and especially the Cold Dome, its dynamics, variabilities and uncertainties, as well as impacts

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of this environment on low-frequency (100 to 1000Hz) acoustic propagation. The dynamics in this region is under the influence of a large number of processes that can occur simultaneously, very energetically and on multiple scales. These processes and associated features include:

- the Kuroshio, a western boundary current interacting with complex topography and influenced by larger-scale Pacific variability;
- ocean responses to atmospheric forcing including Typhoons;
- mesoscale and sub-mesoscale variability, such as the Kuroshio's meanders and eddies, formation of semi-permanent features (Cold Dome) and sub-mesoscale eddies, filaments and thin layers;
- Taiwan Strait shelf jets and currents and their effects on Kuroshio intrusions;
- and, finally, surface and internal tides, internal waves and solitons.

These rich dynamics and processes constitute the larger oceanography context of our effort. They lead to significant uncertainties in and around the Cold Dome region.

The methods and schemes developed for the DRI are generic, but are driven by the above dynamics. The technical research includes: new scientific computations and sensitivity studies; predictability quantification using ESSE; multiply nested high-resolution ocean and acoustic modeling; uncertainty estimation using new prognostic equations and ESSE ensembles; coupled data assimilation and model improvements; observation system simulations and adaptive sampling to exploit uncertainties; and, end-to-end multi-model systems. The uncertainty research builds on the efforts of the UNcertainty and Interdisciplinary Transfers through the End-to-End System (UNITES) Team which contributed to understanding, characterizing and quantifying uncertainty in the ocean environment and assessing its impact on sonar system performance in the littoral. Novel uncertainty work in this new project includes research towards prognostic uncertainty equations, real-time uncertainty estimation and real-time uncertainty exploitation, in each case for acoustic-oceanographic fields.

WORK COMPLETED

Reanalysis of IOP09: A reanalysis of the IOP09 simulations was carried out in which two-way nesting was employed to improve resolution in the canyons, around the primary observation area and around the northern tip of Taiwan. Various aspects of these simulations were tuned during the course of the reanalysis. The conditioning of the topography in the small domain was revisited to control some artificial instability generating sites while preserving the important features (including the complex canyon structure). The distribution of vertical levels was reworked to improve the accuracy and numerical stability of the simulations. The initialization procedure was improved (tuning objective analysis scales, adjusting the combination of *in situ* data, SSH and climatology for nesting and improving the consistency in the tidal fields between the two modeling domains). The results of this analysis were published in Haley and Lermusiaux (2010).

Tidal modeling: Two main modifications have been made in the way we prepare barotropic tidal fields for use in initializing/forcing the 4D MSEAS model. First, we have explored and tuned new bottom drag formulations that are used both in the barotropic tidal inversion and in the MSEAS PE model. These formulations include different combinations of the tidal velocity, the bottom topography and the reduced slope of the bottom topography. The second area of improvement has been in our code to ensure that the barotropic tidal fields provided to the MSEAS PE model satisfy the B-grid discretization of the barotropic continuity equation. We now solve a least-squares minimization of perturbations to both the barotropic tidal velocity and the tidal surface elevation, constrained by the requirement that the final barotropic tidal fields satisfy the B-grid barotropic continuity equation on the MSEAS PE model grid (appendix 2.3.1 in Haley and Lermusiaux, 2010).

Ocean-Acoustics Dynamics for the Pilot Study: We continued to use coupled oceanographic (4D)-acoustic (Nx2D) full field simulations to explain and quantify the mean and variability of mid-frequency sound transmission losses observed during the QPE 2008 Pilot experiment northeast of Taiwan. Employing an ensemble approach, we studied the sensitivity of our results to uncertainties in several factors; including geoacoustic parameters, bottom layer thickness, bathymetry, and ocean conditions. The results of this work were published in Lermusiaux *et al.*, (2010).

Uncertainty Forecasting for Coupled Ocean-Acoustics: A publication (Evangelinos et al, 2010) was completed on the use of many-task computing for coupled ocean and acoustic uncertainty predictions. The use of Sun-Gridengine was especially useful to distribute all N-by-2D acoustic simulations in parallel. Ocean fields and guidance on principal components were also provided in Lin et al (2010).

Coupled Ocean and 3D-Acoustic Simulations in Canyons. We also completed a comprehensive set of computational, sensitivity and dynamical studies on the coupling of ocean simulations with 3D acoustics (Figs 6 and 7). Our focus was on the North Mien Hua Canyon. We employed an updated version of FOR3D. Computational studies included the type of acoustic boundary conditions employed, as well as the resolutions in range and azimuth.

RESULTS

Reanalysis of IOP09: Out of the ensemble of month-long 2-way nested simulations that made-up the reanalysis, some of the canonical results are described using a representative simulation. Fig. 1 shows the relative vorticity computed at 50 m depth, 10 days (0000Z on 28 Aug 2009) into the simulation. The fine domain (right panel) captures the vortex generation of the Kuroshio passing over the I-Lan ridge (starting from Taiwan at 24.5N, 121.9E and extending to the southeast). A well-developed vortex wake is clearly visible trailing to the northeast off of Yonaguni Island (24.45N, 123E). Downstream of the I-Lan ridge, the vorticity field shows an eddy trapped between the Kuroshio and the shelf. The various off-shelf vorticity wakes generally follow the Kuroshio to the northeast, out of the domain. On the shelf, the interaction of tidal currents with topography produces a tight vorticity signal along the 50m isobath just north of Taiwan. Across the mouth of the Taiwan Strait, we find another (weaker) interaction of tidal currents and bathymetry, aligned north by northeast roughly along the 80m isobath. In the coarse domain (left panel), the averaged versions of the small domain features are maintained. The vortex wakes streaming out of the small domain are smoothly continued in the external portions of the large domain. The 2-way nesting also maintains the wake off Yonaguni Island in the large domain although the island is not explicitly represented in the large domain. Outside the small domain, similar wakes, topographic generation and eddies are present, though of necessarily larger scale. We have also compared 2-to-3 day forecasts with *in situ* temperature and salinity data (Newhall *et al.*, 2010). We find that the 2-way nested simulations have RMSE and biases that are on average 10 percent smaller than a stand-alone run (coarse domain alone, without the nested domain). Such higher-resolutions runs are also necessary for internal tide predictions and acoustic simulations (Lermusiaux *et al.*, 2010).

Tidal Modeling: We found that the new bottom drag formulations (particularly the formulation based on the velocity and the reduced slope) improved our results in two ways. First, in the inverse procedure, using the new formulations made it easier to control an unrealistic resonance in the diurnal components in the Strait of Taiwan. This, in turn, allowed the tuning of the bottom drag parameters to better fit the limited available current meter data. The second area of improvement was in the (4D) MSEAS PE simulations. The new bottom drag formulations provided superior control to instabilities generated off the NE tip of Taiwan (again the combination of velocity and reduced slope performed best). For the adjustment of the barotropic tidal fields to the discrete B-grid conservation of mass, using the new least-squares formalism allowed the inclusion of a simple velocity penalty term. This term proved instrumental in controlling unrealistically large isolated velocities being created in spots along the Taiwan coast by previous heuristic algorithms that merely added a velocity perturbation.

Ocean-Acoustics Dynamics for the Pilot Study: We investigated uncertainties in geoacoustic parameters in both the shelf and shelfbreak acoustic simulations. We found that the sediment layer's properties led to larger but isotropic variations on the shelf (event A) and smaller but more anisotropic variations over the shelfbreak (event B) (Fig. 2). Our hybrid depth-dependent geoacoustic model for the shelfbreak and sand model for the shelf best agreed with the observations. Our investigations on the thickness of sediments showed that it had some limited effects (up to about 2 dB), but only on the up-slope transmissions on both events A and B. We also estimated the pdfs of the TL in response to these geoacoustic parameter uncertainties. We found that uncertainties in sediment sound speeds led to skewed or bimodal pdfs for the TL (Fig. 3).

By comparing different sources and resolutions of accurate bathymetric data sets, we derived a statistical model of bathymetric uncertainties. Sensitivity studies on these uncertainties revealed that TL uncertainties (up to 1-dB standard deviation) were proportional to the 1%–4% bathymetric uncertainties but that the mean TL curves did not change their shape as a function of bearing angles (Fig 4). The coupled oceanographic–acoustic modeling studies uncovered a surprising result: initial transport conditions in the Taiwan Strait can affect acoustic transmissions downstream more than 100 km away (Fig. 5). We found that it affected the shelfbreak region (1-dB standard deviation, up to 5 dB) more than the shelf region (0.5-dB standard deviation, up to 3 dB). This is because the shelfbreak ocean dynamics is more sensitive to this transport than the shelf dynamics. The TL pdfs showed similar properties.

Uncertainty Forecasting for Coupled Ocean-Acoustics: In Evangelinos et al (2010), we find that many-task computing is required for coupled uncertainty predictions if acoustic computations are completed for a large set of angles, positions and frequencies. Even though each acoustic computation is very fast (a few minutes on a 2.4 GHz PC), the many parameters lead to distributed computing.

Coupled Ocean and 3D-Acoustic Simulations in Canyons. Our simulation studies of 3D acoustics in the North Mien Hua Canyon (Fig. 6) clearly show the importance of 3D effects in complex Canyon geometries, with several out-of-plane transmissions (Fig. 7). In addition, 3D acoustic simulations reveal sound intensification just across the Canyon (Fig. 7). This is due to the occurrence of a strong focal point in the forward 3D propagating sound wave as it is reflected by both the complex bottom and the sidewalls of diverse orientations in the sub-sea canyon. The Nx2-D simulations do not allow net energy transfer across adjacent vertical planes and they do not show this intensification. Furthermore, our comparison of 3-D acoustic simulations using a MSEAS range-dependent sound-speed field and a range-independent (averaged) sound speed field shows the importance of coupling 4D ocean in such 3D transmissions. The varying ocean environment needs to be integrated into real-time 3D acoustic prediction schemes. For the computational studies, we found that the use of open-boundary conditions common in ocean modeling can be transferred to, and modified for, 3D acoustic modeling.

IMPACT/APPLICATIONS

Better understanding, quantification and exploitation of environmental and acoustic fields and uncertainties for efficient sonar operations. Better integrate, demonstrate and utilize end-to-end prediction and DA systems.

TRANSITIONS

Multiple approaches, results and data were transferred to members of the DRI, including Taiwanese colleagues. Very useful collaborations also occurred with WHOI. Finally, QPE simulation results have been provided to K. Mohseni and D. Lipinski of the University of Colorado.

RELATED PROJECTS

This effort is linked to AWACS (N00014-07-1-0501) and PLUS research.

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FIGURES

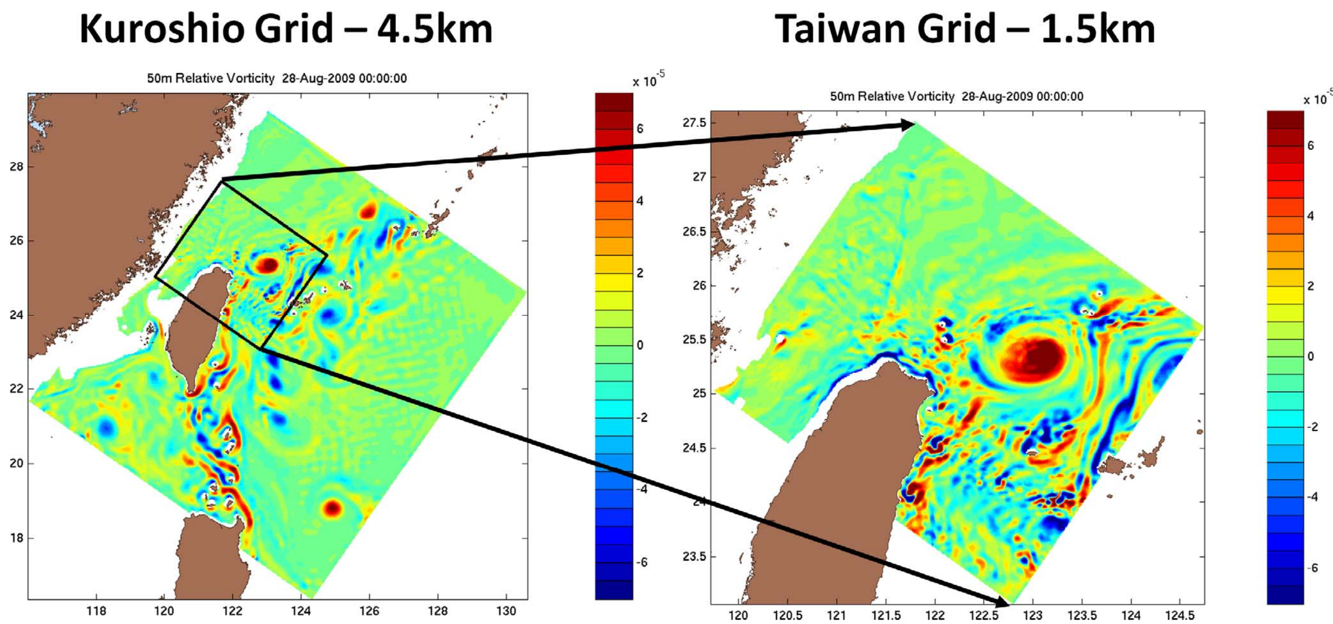

Figure 1. Relative vorticity at 50m in the Taiwan/Kuroshio region for 0000Z on 28 Aug 2009, estimated by our new fully implicit 2-way nesting. This is one of the ensemble simulations we have for the period 18 Aug - 10 Sep 2009. Note the smaller scales maintained in the fine resolution, especially the topographic generation of vorticity as the Kuroshio crosses I-Lan ridge.

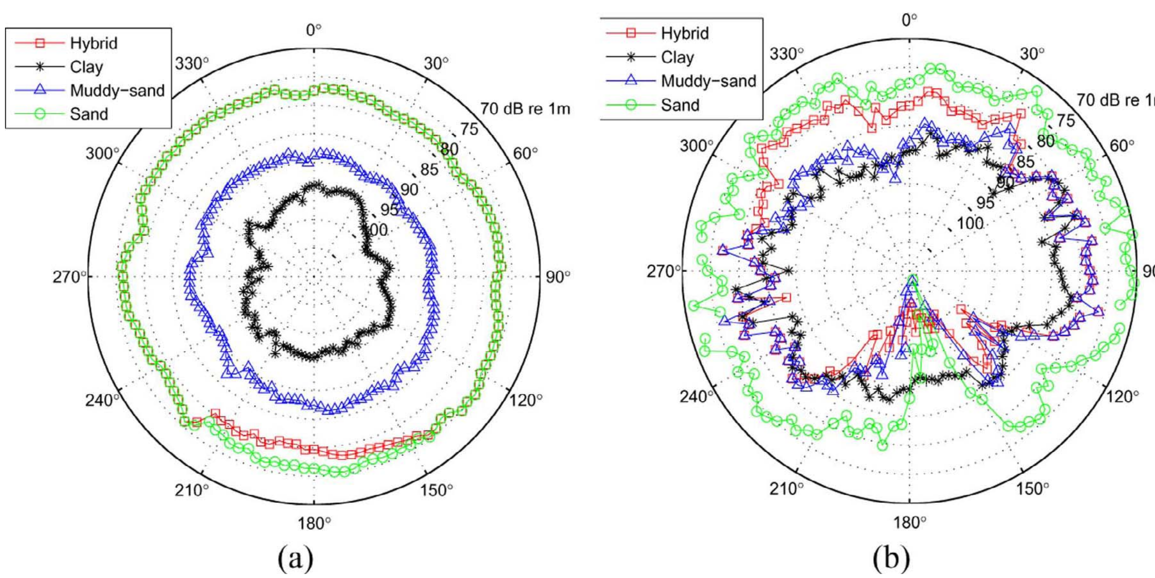

Figure 2. Nx2-D TL simulations of events A and B, illustrating effects of different sediments models (and keeping all other factors constant: in particular, the sediment thickness is set to 20 m). The four different sediments shown are: depth-dependent (hybrid) model with variable sediments, sand, muddy sand, and silty clay. With these sediment variations, one obtains a standard deviation for event A of 9.55 dB and for event B of 5.81 dB. The central ocean fields are at 12:00:00Z, September 8, 2008.

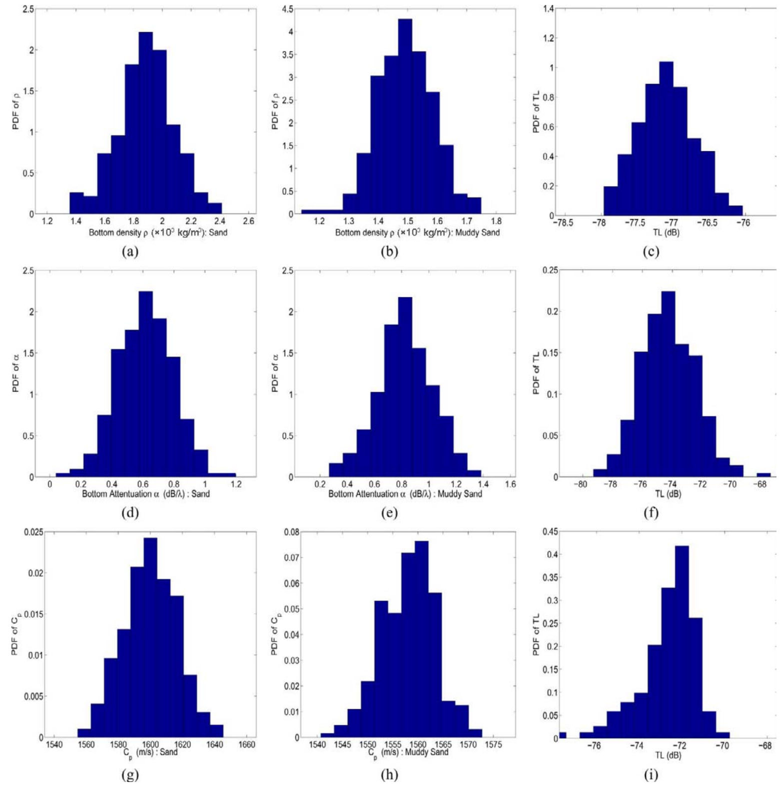

Figure 3. TL uncertainties due to geoacoustics uncertainties, in accord with Tables I and II: (a) pdf of Gaussian realizations of bottom sediment density for sand; (b) pdf of Gaussian realizations of bottom sediment density for muddy sand; (c) pdf of TL corresponding to (a) and (b); (d) pdf of Gaussian realizations of bottom attenuation for sand; (e) pdf of Gaussian realizations of bottom attenuation for muddy sand; (f) pdf of TL corresponding to (d) and (e); (g) pdf of Gaussian realizations of bottom sound speed for sand; (h) pdf of Gaussian realizations of bottom sound speed for muddy sand; (i) pdf of TL corresponding to (g) and (h). The central ocean fields are at 12:00:00Z, September 8, 2008.

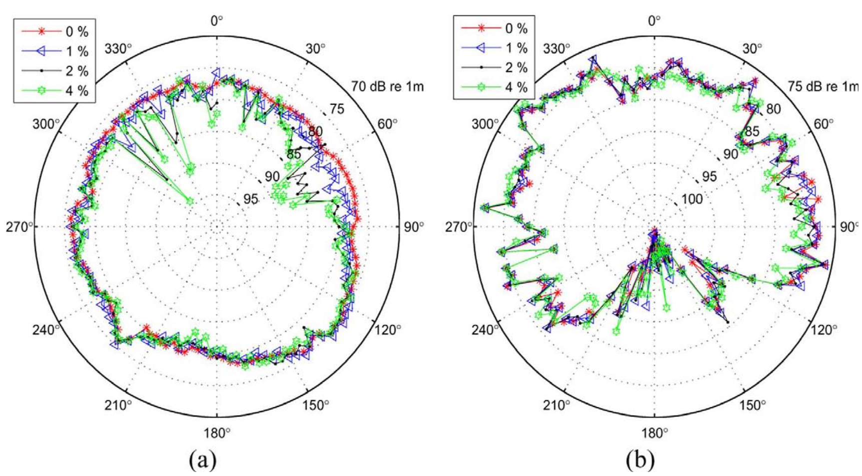

Figure 4. Nx2-D TL simulations of event A (1.25 dB standard dev.) and event B (1.02 dB standard dev.) with different percentages of random perturbation on the 100-m resolution bathymetry data. The normally distributed random noise was added on the bathymetry with a variance proportional to the slope and to the local depth. The central ocean fields are at 12:00:00Z, September 8, 2008.

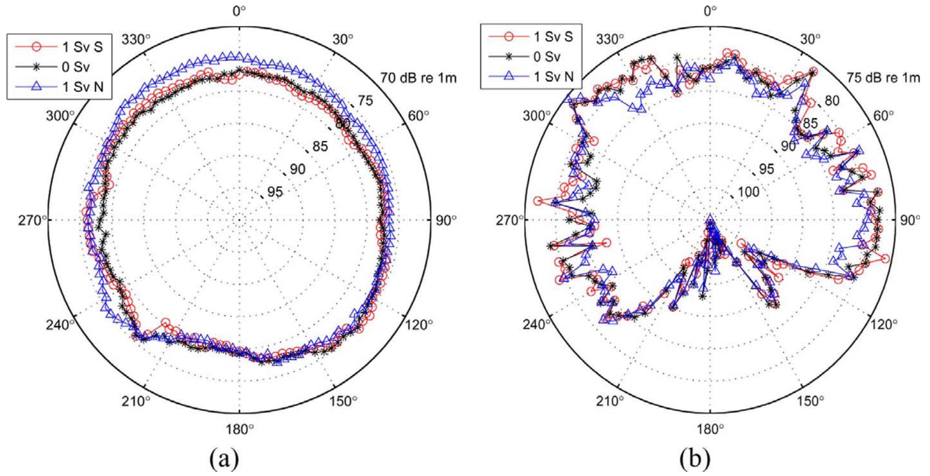

Figure 5. Nx2-D TL simulations of event A (0.58 dB standard dev.) and event B (1.21 dB standard dev.) at 12:00:00Z, September 8, 2008, corresponding to different ocean field predictions (transport conditions between Taiwan and mainland China initialized at +/-1 or 0 Sv) used as inputs for the background sound-speed field.

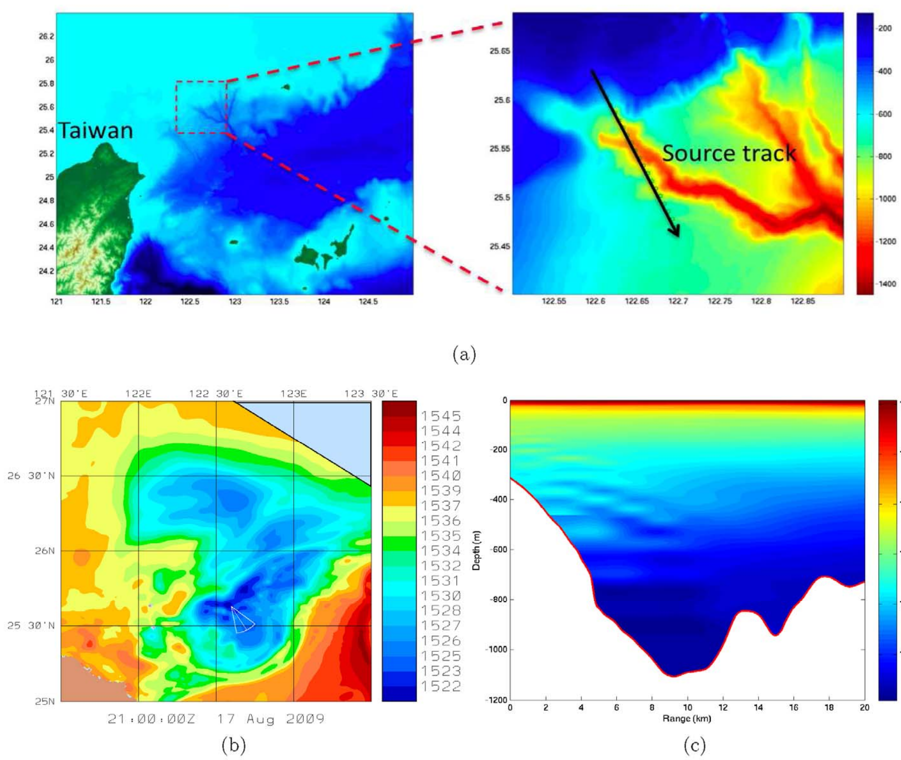

Figure 6. a) QPE experimental region (upper left panel); North Mien Hua Canyon bathymetry overlaid with a simulated OMAS sound source track (upper right panel). b) The sound speed at 30 m depth predicted by the two-way nested MSEAS ocean modeling system on Aug 17, 2100 Z, 2009. The fan shape region with the white color border indicates the acoustic simulation domain in 3-D cylindrical coordinates. c) The sound speed vertical cross section along the simulated OMAS sound-source linear track at the same modeling time of Aug 17, 2100 Z, 2009.

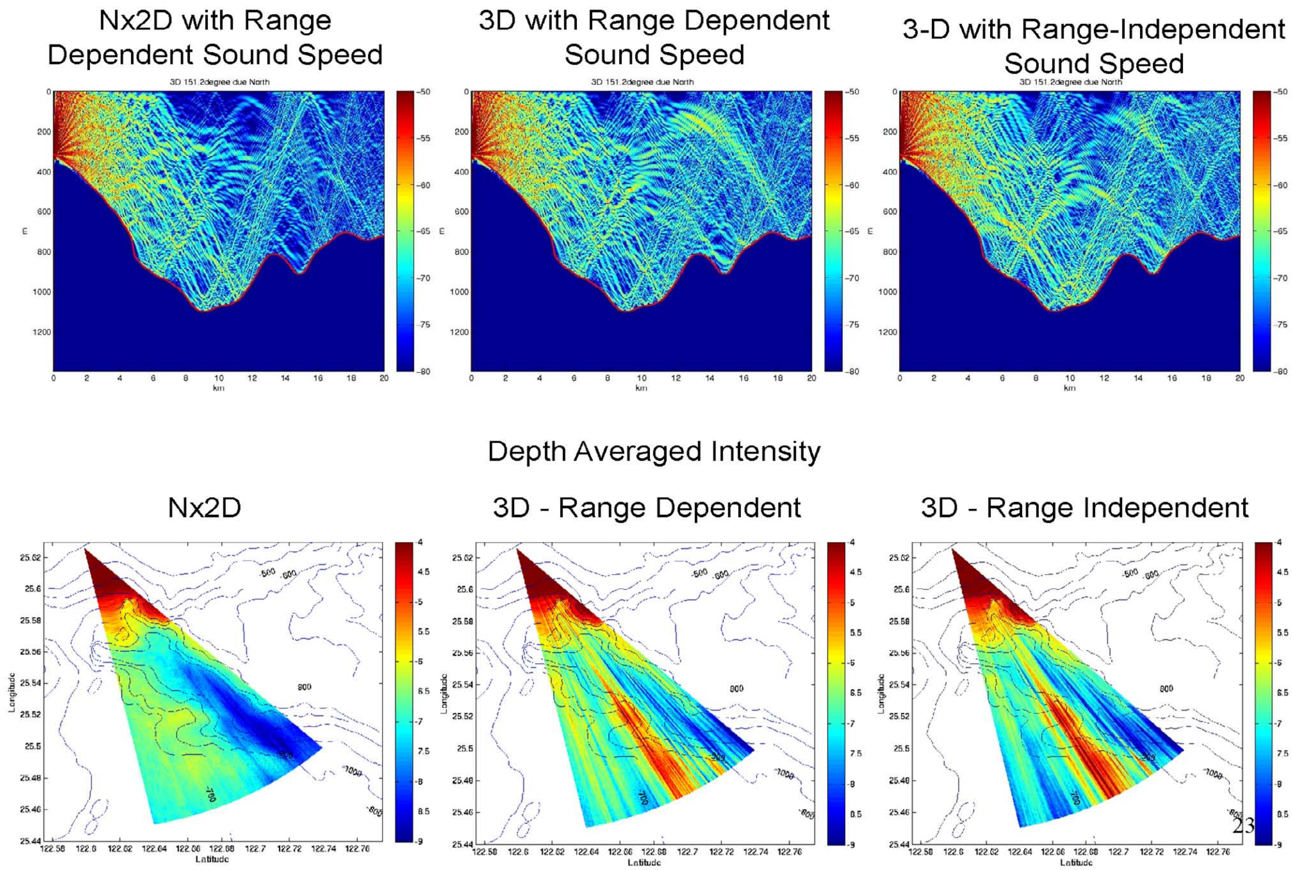

Figure 7. Acoustic 3D and Nx2-D sound propagation through North Mien Hua Canyon coupled to ocean simulations: (a) Nx2-D acoustic simulations: TL as function of range and depth at 151 degree due north; (b) 3-D acoustic simulations: TL as function of range and depth at 151 degree due north; (c) As b), but with a range independent sound speed background; (d) Depth averaged intensity: Nx2-D simulation with range dependent sound speed background; (e) Depth averaged intensity: 3-D simulations with range dependent sound speed background. The intensity scale is decibel referenced to the maximum value; (f) As e), but with a range independent sound speed background.